Lunar Poles
Status of Understanding a Potential Resource

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“The Most Valuable Real Estate in the Solar System”
Overarching Polar Issues

• High visibility
  – Public and professionals are aware of various claims about the value of the poles

• Polar relevance as a resource cannot be resolved using remote sensing
  – Most claims cannot be refuted or confirmed with remote sensing

• *In situ* measurements require an approach unlike current crop of Mars landers and rovers.
  – Engineering challenges of operating Mars-type rovers and landers are extreme and irrelevant to Mars exploration
  – Capabilities of MPF/MPL/MER are largely overkill or irrelevant to the problem--this is not geology

• *In situ* measurements require supporting remote sensing measurements to select analysis sites
Status

Neutron results
Radar results
THE LUNAR POLES EXHIBIT A DEFICIT OF EPITHERMAL NEUTRONS
The only geologically reasonable explanation is an anomalous concentration of hydrogen
The abundance of H is about 200 ppm at the resolution of LP (~50 km), about 2x that in high Ti mare soils.
If the H is confined to permanent shadow and if it is in the form of water ice, then the average abundance in the shadow is 1-2 wt% within the most anomalous LP pixels.
Earth-based radar has imaged several areas believed to be in permanent shade. **No anomalous radar properties are observed in the polar region or shaded regions.**

But, radar is only sensitive to very pure ice, or pure ice with overlain with a thin layer of ice-free soil.
No unusual morphologies are apparent within regions of permanent shade

Current or ancient ice deposits did not leave an obvious geologic overprint
Radar observations and Lunar Prospector neutron measurements are entirely consistent. H in some form must be present at hundreds of ppm in some locations. But, if ice is present it is impure everywhere in the imaged regions to the ~500-m resolution of the data.
“A pox on both your houses”
What about Clementine?

- Clementine bistatic radar data was used to detect a weak signal consistent with coherent backscatter in a low-loss medium associated with the south polar crater Shackleton (Nozette, Lichtenberg)
- Others in the radar community disputed the methodology and results based on an attempted reproduction of the original analysis (principally Simpson)
- The Clementine team disputes the navigation used by Simpson
- Earth based data for portions of Shackleton in common show high values, but not clearly anomalous
- Roughness is a plausible explanation for the Clementine bistatic radar results
What about Clementine?

• Despite the spirited exchange, the Clementine detection has not been definitively refuted. However, ubiquitous Mercury-like deposits do not exist in the imaged regions.

• The controversial interpretation of the controversial bistatic detection as ice has not been ruled out by new earthbased data. Mercury-like deposits cannot be ruled out in the unimaged regions because the imaged regions may not be representative of the unimaged areas. The areas accessible to Arecibo may be blow-torched by the Earth’s magnetotail; Clementine may have glimpsed a deposit shielded from this influence.

• Conclusion: Regardless of the controversy surrounding the detection, its inherent weakness and the existence of plausible alternatives to the ice hypothesis render the contribution of Clementine experiment largely ineffective with respect to the understanding of the lunar poles.
“The garbage dump of the solar system”
Outstanding Questions Remain

• What is the physical and chemical state of the hydrogen?
• Are other volatile elements or compounds present?
• What is the concentration of volatiles at spatial scales relevant to resource recovery?
• Does temperature reliably predict the distribution of volatiles?
Outstanding Questions Remain

• What is the physical and chemical state of the hydrogen?

• Hydrogen has been proposed to be in the form of:
  – Adsorbed or diffusively trapped H2
  – H2O or methane clathrate
  – Methane ice

• Chemical state is critical to resource utility
Outstanding Questions Remain

• Are other volatile elements or compounds present?
  – Hydrogen must be an indicator of a more complex volatile deposit
Possible Sources of Lunar Polar Volatiles

- Comets
- Solar Wind
- Asteroids
- The Moon
- Interplanetary Dust Particles
- Giant Molecular Clouds
- Earth
Lunar Polar Volatile Inventory

- Each potential source provides a suite of volatile elements and compounds
- **No source provides only hydrogen**
“It's not the heat, it's the humidity”
Cold trapping is assumed to control volatile distribution
South Polar deposits seem closely correlated with areas of permanent shade.

North Polar hydrogen distribution is more enigmatic.
North Pole:

Large flat-floored craters show low hydrogen abundances relative to adjacent terrain.
North Pole:

Neutron deficit is largely confined to surrounding rough terrain.
North Pole Hypotheses:

1) Rough terrain promotes low temperatures
   • Small declivities better shielded from sunlight
2) Smooth terrain promotes loss mechanisms
   • More susceptible to sputtering, more integrated radiation load
3) Relic deposit embayed by subsequent processes
   • H-bearing material must be refractory
     • Bound water
     • High molecular weight organics
   • Must be very ancient (embayed by light plains)
Natural *in situ* production of "refractory" compounds is plausible

- Production of clay minerals in wet, hot ejecta blankets owing to impacts into ice rich targets during Mercury-like era
- Production of high molecular weight organics from CHON and proton irradiation
  - CHON derived from ices or solar wind ions
“To the Batpoles, Robin”
The Next Step

We know:
- Hydrogen is present in anomalous concentrations at the poles at 50 km resolution
- Thick ice deposits are absent in the imaged areas of permanent shade

We can assume:
- Lyman α and micrometeorites almost certainly have desiccated the uppermost few centimeters

We do not know:
- The volatile inventory
- The concentration of volatiles at resource recoverable scale (~100m)
- The position of any features to 10’s of km laterally and 5’s of km vertically in the polar regions
- The degree to which temperature controls the distribution
The Next Step

Orbiter Goals:

Establish the geodetic knowledge necessary to address problems at high resolution
Determine the morphology at scales relevant to safety of landed experiments
Refine the knowledge of volatile distribution
Determine the controls on volatile distribution to allow prediction

Lander Goals:

Determine the volatile inventory
## Potential Orbiter Payloads

<table>
<thead>
<tr>
<th>Task</th>
<th>Instrument</th>
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</thead>
<tbody>
<tr>
<td>Establish the geodetic knowledge necessary to address problems at high resolution</td>
<td>LIDAR, LIDAR/Stereo, Radar Interferometry</td>
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<tr>
<td>Determine the morphology at scales relevant to landing safety</td>
<td>SAR, Low light level optical imaging</td>
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<tr>
<td>Refine the knowledge of volatile distribution</td>
<td>Collimated neutron spectroscopy</td>
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<tr>
<td>Determine controls on volatile distribution to enable prediction</td>
<td>IR or microwave radiometry</td>
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The Lander Problem

- Lyman $\alpha$ and micrometeorites almost certainly have desiccated the uppermost few centimeters
- Landed science must access the zone between 0.1 (assumed "dry") and 1 m (depth of LP measurement)
- Trench, drill or mole in the dark at 50 kelvins or,
- Get the depth instantly for free with a penetrator
<table>
<thead>
<tr>
<th>Determine the volatile Inventory</th>
<th>Measurements at multiple sites (if $T$ is a poor predictor of distribution)</th>
<th>Several landers</th>
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<tbody>
<tr>
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<td>Chemical state of hydrogen</td>
<td>Mass spectrometer, IR spectrometer, H gas detector</td>
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<tr>
<td></td>
<td>Detection of all volatile species to lunar background levels</td>
<td>Mass spectrometer</td>
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<td></td>
<td>Detection of involatile H-bearing and other resource-relevant, polar peculiar, species</td>
<td>DSC/MS</td>
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“Perfection is the enemy of good enough”
Polar Science vs. Applied Science

Measurements and Research Required for Polar Science

Measurements Proposed Here
Polar Science vs. Applied Science

Identity of sources
Inferences regarding sources
Volatile transport
History of illumination
Evolution of the Sun

Volatile inventory
Volatile distribution
Dependence of distribution on temperature
“That’s All Folks”